Control System Characteristics of a Nonequilibrium Plasma Jet

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The correlations between characteristics of the plasma jet such as gas temperature, radiation intensity, electron temperature and electron number density, and operation conditions such as discharge current, applied magnetic flux density, gas flow rate and gas mixing rate are clarified experimentally. There is a linear interrelation between radiation intensity and the two operation parameters of discharge current and magnetic flux density. A feedback control system is constructed utilizing the obtained correlations and is verified the system characteristics. The wide range of the radiation intensity can be controlled by discharge current in this system and also the radiation intensity can be controlled with fast response by applying a magnetic field.

1. Introduction

Plasma flow is used as a multifunctional medium, because it has high energy density, chemical reactivity and variable transport properties. Therefore, plasma flow has been utilized for environmental purification and material processings [1]-[10]. The improvement of the applications and the establishment of the advanced plasma processes are very important. However, only a few papers [11] have been published about control systems of thermal plasma flow because of its complex flow system, in which thermodiffusion, particulate and electromagnetic fields are superposed [12]-[17].

The primary objective of the present paper is to clarify experimentally the correlations between the plasma jet characteristics and the operating conditions in order to pick up the important controlled and manipulated variables. Construction of control system and verification of its characteristics are the second objectives to establish the intelligent control system for plasma jets.

2. Experimental setup and procedures

Figure 1 shows the schematic of the experimental apparatus. It consists mainly of a DC plasma torch, a test pipe, solenoidal coils and a vacuum system. The primary gas injected with weak swirl is Ar of 30-50 SL/min, discharged at 0.9 kW. The secondary gas injected tangentially to the nozzle is Ar, He or N₂, 30-50 SL/min, discharged at 3.6-6 kW. The third gas injected radially to the nozzle is Ar as the disturbing gas. The test pipe diameter is 80 mm, keeping an operating pressure between 600 to 1000 Pa. The maximum axial applied magnetic flux density is 0.44 T. As for the measurements, gas temperature is measured by a W-Re thermocouple and radiation intensity is measured by a Si photodiode through the integration circuit of 0.3 s, respectively. Electron temperature and electron number density are measured by a Langmuir probe [18]. The sampling rate of the I-V curve from the Langmuir probe is 100 Hz, and the electron temperature and the number density analyzed by averaging 10 samples of the I-V curves. The measuring location is at the center of the pipe and at 426 mm downstream from the nozzle exit.

Figure 2 shows the schematic of a feedback control system for a plasma jet. The control system consists of a detected element for monitoring controlled variables such as gas temperature, radiation intensity, electron
temperature and electron number density, a control element for outputting the PID control signal and a final control element for manipulated variables such as discharge current for the second nozzle, magnetic flux density, gas flow rate and gas mixing rate. The steps for constructing the plasma control system are (1) extracting the key factor for the control by clarifying the relation between the controlled variables and the manipulated variables and the speed of response of the manipulated variables, (2) deciding the transfer function of PID action by the step response of the controlled variables to the manipulated variables, and (3) verifying the characteristics for the constant value control and the disturbance suppression control.

3. Experimental results and discussion

3.1. Interrelations between the control variables and the manipulated variables of the plasma jet

Figure 3 shows the controlled variables with the discharge current for the different magnetic flux densities. Electron number density and electron temperature increase steeply with discharge current due to the active
ionization. Radiation intensity shows a linear interrelation to discharge current. These result from the increase in the total enthalpy of the plasma jet.

Figure 4 shows the controlled variables with the magnetic flux density for the different discharge currents. The same tendency is shown in the electron temperature and the radiation intensity each other. Especially, a linear correlation is obtained between the radiation intensity and the magnetic flux density. These result from the restraint of radial diffusion of electrons across the magnetic line of force. On the other hand, gas temperature shows the weak correlation to the magnetic flux density.

Figure 5 shows the controlled variables with the secondary gas flow rate for the different primary gas flow rates. The values of the controlled variables decrease with the increase in the gas flow rates. Especially, the radiation intensity and electron number density show large variation at the small primary gas flow rate, but small variation at the large gas flow rate. These are caused by the decrease of charged particles with the decrease in the enthalpy of the plasma flow.

Figure 6 shows the controlled variables with the mixing rate of He or N₂ gas. The radiation intensity and electron number density are decreased steeply even by mixing N₂ gas of 5% due to the large energy consumption for the dissociation. On the other hand, the gas temperature increases and the radiation intensity decreases with the increase in the mixing rate of He.

3.2. Step response

Figure 7 shows the step responses of the controlled variables to the discharge current. The radiation intensity and the electron number density responds quickly and adequately to the step input of the discharge current. This is the reason why the relaxation time of the luminescence is very short compared with the variation time of the discharge current and the ion and the excited atom are the radiation source. The gas and electron temperatures show the weak interrelations.

Figure 8 shows the step responses of the controlled variables to the magnetic flux density. The radiation intensity and the electron temperature have quick and high rate responses to the step input of the magnetic flux density.
Fig. 7. Step responses of controlled variables to the discharge current, (a) gas temperature, (b) electron temperature, (c) radiation intensity, (d) electron number density. ($\beta = 0 \text{ T}$)

Fig. 8. Step responses of controlled variables to the magnetic flux density, (a) gas temperature, (b) electron temperature, (c) radiation intensity, (d) electron number density. ($I_d = 100 \text{ A}$)

The summary of the correlation between controlled variables and manipulated variables are as follows. The important controlled variables are (1) radiation intensity and electron number density to the discharge current, (2) radiation intensity and electron temperature to the magnetic flux density, (3) radiation intensity to gas flow rate, and (4) radiation intensity and gas temperature to gas mixing rate. Furthermore, the evaluation of the controlled variables are that (1) the radiation intensity shows high reproducibility and responsibility, (2) gas temperature shows high reproducibility but low responsibility, and (3) electron temperature and electron number density show high responsibility and low reproducibility. From the summary, the discharge current and the magnetic flux density are adopted as the manipulated variables, and the radiation intensity as the controlled variable.

3.3. Feedback control system

Figure 9 shows the block diagram of the feedback control system. The constant value control using PID control system is constructed. The transfer function $G_c$ for PID control system is given by equation (1) as follows [19]:

$$G_c(s) = K_p \left( 1 + \frac{1}{T_i s} + T_d s \right)$$

(1)

where $K_p$, $T_i$, $T_d$ are gain constant, integral time and derivative time, respectively. The transfer function, $G_p$, of control system for the discharge current (2) or the magnetic flux density (3) is given approximately by considering the first-order lag element or time-dead element as shown below:

$$G_p(s) = \frac{0.044}{1 + 1.2s} e^{-0.5s}$$

(2)

$$G_p(s) = \frac{1.5}{1 + 1.63s} e^{-0.35s}$$

(3)

The critical sensitivity $K_p$ and the continuous oscillation period $T_p$ are decided by using ultimate method. When the discharge current and the magnetic flux density are used as the manipulated variable, $K = 30$, $T_i = 2.3 \text{ s}$, $T_d = 0.58 \text{ s}$, and $K_p = 0.8$, $T_i = 1.0 \text{ s}$, $T_d = 0.09 \text{ s}$, respectively. The parameters are decided by using ultimate method.
3.4. The constant value control characteristics

Figure 10 shows the time responses of radiation intensity under PID control. When the radiation intensity is set at 2.4 μA, the discharge current control shows the overshoot rate of 15.8% and time constant of 4.7 s with small electrical current as the manipulated variable. However, the magnetic flux density control shows overshoot rate of 2.0% and time constant of 1.9 s with large electric current as the manipulated variable. These results imply that the discharge current control is applicable to wide range with small electrical current, but the magnetic flux density control is applicable to high speed response and precise control with large electrical current.

3.5. The disturbance reducing control characteristics

Figure 11 shows the indicial responses to the radial injection of the third gas of Ar as the disturbance. The discharge current control shows the low stability, but the magnetic flux density control shows the high speed of response with stability.

3.6. The fluctuation suppressing control characteristics

Figure 12 (a) and (b) show the controlled radiation intensity to have the same radial profiles by changing discharge current under the different magnetic flux density, and the magnetic suppression effect on the fluctuation of the radiation intensity, respectively. Here, $I_{rms}$ is the rms of 200 samples of the radiation intensity. The radiation fluctuation intensity is clearly decreased in the applied magnetic field. This implies the possibility to suppress fluctuation of plasma flows by applying magnetic field.
Fig. 12. (a) Controlled radiation intensity to be same radial profiles by changing discharge current under the different magnetic flux density, (b) magnetic suppression effect on the fluctuation of the radiation intensity.

4. Conclusion

In the present study, the interrelations between the controlled variables of the plasma jet characteristics and the manipulated variables of the operating conditions are clarified. The feedback control system for the plasma jet is successfully constructed corresponding to the command. These results imply the possibility of the intelligent control system. The results are summarized as follows. (1) Radiation intensity is adopted as a controlled variable due to high response and reproducibility. (2) Discharge current and magnetic flux density are adopted as manipulated variables, and the individual control characteristics are clarified for the discharge current control and the magnetic flux density control. (3) Fluctuation of the plasma jet can be suppressed by applying the magnetic field.

Acknowledgments

The present study was partly supported by the Japan Society for Promotion of Science. The authors wish to thank Professor T. Hayase for valuable discussion and technician Mr. K. Katagiri for setting up the experimental apparatus in the Institute of Fluid Science, Tohoku University.

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